Seismic Response and Wavefield Characterization Using a Very Dense 2D Seismic Array on an Active Landslide (Cavola, Italy)

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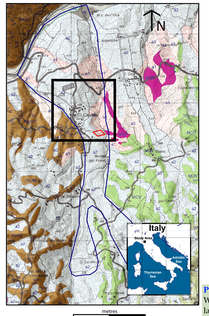
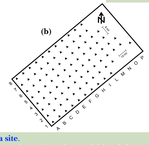
INTRODUCTION

A dense 2D array (94 broad-band stations) was installed in a grid-like configuration over a 130x56 m area on the active landslide of Cavola in northern Apennines, Italy. Outcropping rocks consist of highly fractured marl and muddy and sandstone turbidite dated about 40 millions years. These units are covered by a 4-km long landslide with maximum thickness more than 60m. In historical times there are three instances of activity triggered by meteorological events, with the 1960 event being the most destructive, involving an area of 1.3 km^2 and partial destruction of the Cavola village.
The landslide structure beneath the array was reconstructed by means of active and passive seismic surveys, in-situ velocity measurements and geoelectrical tomography obtaining clay thickness ranging from 0 to 45 m and with average shear-velocity of 360 m/s.
To investigate how the direction of wave propagation and the incidence angle interact with the location of the reference site, we have compared spectral ratios from synthetics and earthquakes computed at two opposite reference site. We have modelled propagation in a 2D model inferred from the geophysical prospecting, for SH and PSV waves with angles of incidence of 0, ±5, ±10, ±20, ±30, ±45, ±60, ±90°, where 0 and 90° are respectively vertical and horizontal incidence, except that ±90 denotes Rayleigh waves in the PSV case.
Moreover, the long data records (3 months of continuous recording) allow investigation of properties of ambient noise in terms of temporal stability and wavefield composition. We find that local industrial sources affect the horizontal-to-vertical spectral ratios on noise (HVNSR) and their interpretation in terms of resonant frequencies. Analysis of noise polarization is also performed, revealing different patterns depending on the nature of the noise source.

Panel A — The Cavola experiment



Pictures taken during the experiment (19 July - 21 October 2004).
With the aim to study the propagation of seismic waves through the Cavola landslide body[1], a very dense 2D seismic array was set. NERC SEIS-UK [2] provided us a hundred Guralp CMG-6TD 3-component broadband sensors (natural period 30s) that were preliminary tested through the standard Huddle Test (**a**). 94 sensors of 100 were used for the seismic array.
The deployment was realized by burying the sensors in 70-100cm deep holes (**b**) and by using solar panels to power the stations (**c**).
Three month of data (900 Gb) have been recorded and will be soon available from the IRIS Data Management Center at www.iris.edu.

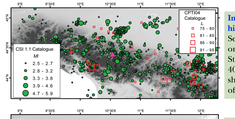


(a) Geology of the Cavola site.
The study area lies in the northern Apennines, a fold and thrust belt which started forming during the Cretaceous age. The main outcropping units, fractured flysch and clayey melanges, belongs to Middle-Late Eocene (Monte Piano) and Late Eocene-Early-Oligocene (Ranzano formation). They are covered by a major landslide, 4km long and 600m thick at the foot.
The landslide consists of a clay body sliding over mudstone-shale basement, and has been triggered several times in the last century by meteorological events and could be reactivated by large earthquakes.

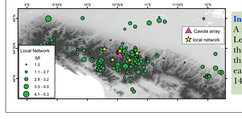
(b) Geometry of the Cavola array
The array geometry was designed taking into account the frequency range of interest deducted by preliminary noise measurements, and the morphology and logistic condition of the investigated area.
The grid-like configuration has a station spacing of 10m in the NE-SW direction and 8m in the NEWSE direction.
The total size of the array is 130x56m.
The station in the P line (called P5) lies on the Monte Piano formation, few meters apart from the landslide.

Digital elevation model of the array area and horizontal-to-vertical spectral ratios on noise (HVNSR) for stations within the array area.
An electronic geodimeter was used to measure the elevation of the array area. The difference between lines A and P is about 30m.
HVNRS show peaks in the 3-4.5 Hz frequency band with a sistematic shift of the resonance frequency linked to surface elevation. At the highest elevations we found the lowest peak frequencies.
Frequency variation of HVNSR peaks corresponds to a decreasing thickness of the landslide deposits moving from top (line A) to bottom (line P).

Picture showing the array area (taken from south)
Lines from A to E of the array are deployed in the steeper part of the landslide, whereas lines from F to L are set on a flat area. Lines O and station P3 are separated by a stream (close to the trees on the right) that represents the end of the landslide.

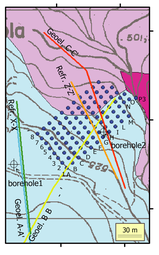


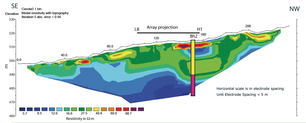
Instrumental seismicity from CSI catalogue (1981-2002) with M>2.5 and historical seismicity with I>VII MCS from CPTI04
Seismicity is evenly distributed along the Apennines and is mainly of crustal origin.
Strong earthquakes (IX-X MCS) occurred near Cavola in the past (distance 40km from the landslide). Very high intensities of earthquake ground shaking are expected to occur at Cavola on a time scale of several hundreds of year.



Instrumental seismicity recorded during the Cavola experiment
A microearthquake network (5 portable Reftek 130 receivers coupled to Lennartz-1Hz seismometers) was installed in the vicinity of the Cavola array throughout the experiment [1], with the aim to reduce the detection threshold and improve on the quality of location of small magnitude earthquakes by INGV national seismic network.
144 earthquakes were detected and localized.

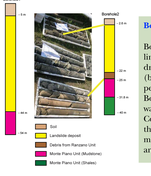
Panel B — Geophysical prospecting



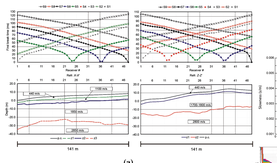


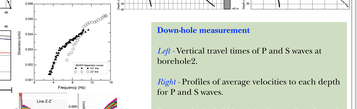
C-C' geo-electrical profile, showing the location of borehole2 and array station
Three multielectrodic surveys with 5m uniform electrode spacing and a maximum lenght of 315m were performed.
The C-C' profile is the best one in resolving the shape of the landslide.
Although the quality of data and of inversion is quite good, several factors limit the resolution in resistivity and then the correct reconstruction of the landslide: the limited depth of investigation, the weak resistivity-contrast between the landslide body and the substratum, and the complexity of the topography that is not fully modelled by the commercial softwares used for the inversion.
Nevertheless, the geolectrical survey gives information on the shape of the landslide, indicating that its thickness decreases down-hill.

The Cavola site, including basement and landslide geology, location of boreholes and geophysical measurements
The study area was deeply investigated through the collection of all the available information, in particular boreholes penetrating the bedrock. Moreover, new geophysical surveys were performed, including geoelectrical, refractrion, down-hole measurements and surface wave analyses (MASW and NASW).
Finally a reconstruction of the landslide body and a characterization of the shear-wave velocity has been carried out. From the different approaches a consistent picture of the depths and seismic velocities for the landslide has emerged.



Borehole logs
Borehole1 was an existing borehole close to line A of the array, whereas borehole2 was drilled during the Cavola experiment (between lines G and H), and used to perform down-hole measurements (see next). Both boreholes reached the bedrock, which was logged as Monte Piano Formation.
Consistently with the noise measurements, the landslide deposits found in the boreholes, move from 44m at the top to 25m at middle array area.





Refraction surveys and surface wave analyses
X-X' and Z-Z' are two conventional P-wave seismic refraction profiles acquired to complement the down-hole measurements.
The two profiles were close to the two boreholes and were also processed using the Multi Channel Analysis of Surface waves (MASW for Z-Z' profile) and the Noise Analysis of Surface waves (NASW for X-X' profile).
(a) Results of P-wave refraction for X-X' (left) and Z-Z' (right). Both profiles identify a thin low velocity layer above a faster unit with P waves velocity ranging from 1700 to 1850 m/s. These two layers comprise the landslide body overlying the bedrock characterized by a Vp velocity of 2800-2850 m/s.
Bedrock depth ranges between 30 and 39 m and 15 and 25m for lines X-X' and Z-Z', respectively.
(b) MASW-NASW results . In the upper part the dispersion curves for lines X-X' and Z-Z' is derived using f-k techniques. In the middle and bottom part the correspondent velocity profiles are shown. Results are in agreement with P-wave refraction and the down-hole measurements at borehole2. The basement is found at 28m and 44m for Z-Z' and X-X' profile, respectively. Velocities also match satisfactorily.

Down-hole measurement
Left - Vertical travel times of P and S waves at borehole2.
Right - Profiles of average velocities to each depth for P and S waves.
P-wave velocity is 520 m/s in the top 3 m above the water table, 1630 m/s in the body of the landslide, and 2850 m/s in the basement. S-wave velocity is 250 m/s and 625m/s above the water table and in the basement, respectively, whereas it linearly increase (from 300 m/s to 625 m/s) with depth in the landslide body below the water table.

Panel C — Simulations

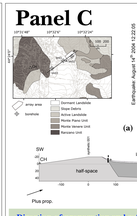
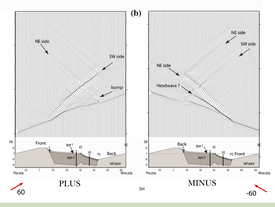


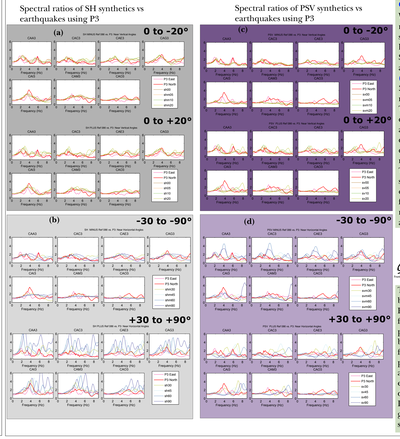
TABLE I: VELOCITY-DEPTH MODELS

Model	Layer	Depth (m)	Density ρ (t/m3)	β (m/s)
Linear Model	1	3	1.9	230
	2	22	1.9	300
	halfspace		2.0	625
Constant Model	1	25	1.9	360
	halfspace	-	2.0	800

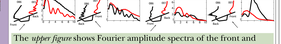


Direction of propagation and reference site.
To evaluate the amplification effects at a site of interest, the choice of a reference site is crucial. With the aim of investigating how the direction of wave propagation and the incidence angle interact with the location of the reference site, we have compared spectral ratios from synthetics and observations computed at two opposite reference site and their corresponding synthetics. We have modelled propagation in a 2D profile for SH and PSV waves with angles of incidence of 0, ±5, ±10, ±20, ±30, ±45, ±60, ±90°, where 0 and 90 are respectively vertical and horizontal incidence, except that ±90 denotes Rayleigh waves in the PSV case.
We have used the impedance-operator-based numerical code developed by Haines and de Hoop [5].

(a) 2D profile used for the numerical simulation. It crosses the Cavola landslide from SW to NE intersecting 14 seismoters. Landslide geometry is an outcome of the multidisplinary approach described in the previous panels. Thicknesses below the array were refined using the resonant frequencies from HVNSR, highlighting the bump under stations A to D. Reference site P3 and its corresponding 086 receiver are at the NE end of the landslide while CH and 001 receiver at the SW end of the landslide.
An example of the waveforms recorded by some array stations (A3, C3, E3, G3, I3, M3, O3 and P3) for the NS component is shown. The waveforms vary markedly in amplitude and shape across the array.
Table I lists the parameters of the linear and constant velocity-depth models used in the simulations.
The linear model is from down-hole measurements: we have proved it but it has produced virtually flat spectral ratios across the array in the SH simulations, though there is better agreement of PSV simulations with the observations because of the contrast in P velocity. Therefore in the following we will show results only from the constant velocity-depth model.
(b) Features of the propagation for SH simulation and incidence angle ± 60° from the vertical. For negative propagation P3 is the front reference site, and CH is the back. For positive propagation CH is the front reference sites, and P3 is the back.
The synthetics show the effect of direction of propagation on the reference site: the front bedrock site is illuminated before the landslide and preserve the wave contents of the incidence wave, whereas the back reference site has diminished amplitude of the incidence wave and later arrivals are also small in amplitude.
Note the much stronger diffractions from the front end than from the back end with respect to the incident wavefield. The first arrivals are the incident SH waves, which are refracted at the base of the landslide and transmited trough the landslide body. Others wave trains are diffracted by the NE and the SW bottom corners of the landslide, and also by the little bump in the basement topography beneath the array.
It is also possible to note later reflections of the diffracted waves travelling horizontally inside the landslide. Many such arrivals are visible in the later part of the time series, and in the negative propagation there is a strong hint of a head wave with higher apparent velocity that has travelled along the top of the basement below the landslide.



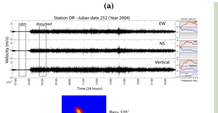
Comparison of H/H synthetics vs earthquakes
We show comparison between observed and predicted spectral ratios referred to P3 (086 synthetic), for SH and PSV simulations subdivided into two main groups: near vertical (0 to 20°) and near horizontal (30 to 90°).
SH synthetics provide a very good match to the data for both positive and negative direction of propagation for incidence angles 0 to 20°
(a). Propagation directions become important for incidence angles 30 to 90°, for which only the minus propagation shows a very good match **(b).**
The PSV seismic motion has a poor match to data for both directions of propagation for incidence 0 to 20° (c), while it has an acceptable match for incidence 30 to 90° again for the minus direction of propagation (d). Note that the minus propagation direction has P3 as the front reference site and CH as the back reference site.
The SH synthetics with CH as reference share some behaviour of spectral ratios at P3: for 30 to 90° incidence angles they match observations for only one direction of propagation, when CH is the front reference site (plus propagation). Therefore using a front reference site appears to be away of obtaining the seismic response in a sort of "absolute" way, at least at Cavola.



The *upper figure* shows Fourier amplitude spectra of the front and back synthetics for PSV and SH seismic motions.
For SH the back site has the spectra de-amplified over the entire frequency range in comparison to the front site for both direction of propagation possibly as a result of partial shadow zones forming behind the landslide. For PSV the back site is strongly amplified for frequency higher than 2 Hz in comparison to the front spectra for plus propagation, whereas for minus propagation the back site is amplified for frequency less than 3Hz. This suggests likely focusing of energy in particular frequency bands behind the landslide, with the differences in shape at the two ends of the landslide.
It is then inadvisable to use a nearby back site as reference because it gives indication on the response of the reference site rather than the site of interest.

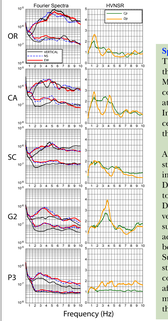
Panel D — Stability and reproducibility of HVNSR

Data
Apart the array stations, 3 extra seismic stations were installed in private houses in Cavola village (OR, CA and SC).
Together with array stations E2, G2, I2 and P3 we used these data to investigate variations of the local ambient noise wave-field composition [4].
Note the presence of a ceramic factory in the upper part and close to station OR.



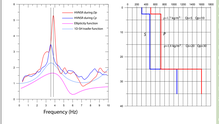
Time variation of spectral content and HVNSR at Cavola
The large dataset recorded at Cavola is a good opportunity to investigate the stability and reproducibility of HVNSR versus daily variations due to human activity.
(a) Example of time series recorded at Cavola (station OR) the September 8, 2004, and spectra of low- and high-amplitude 30-min windows, marked by rectangles.
Note that the amplitude of the signal starts to increase every working day at 3:00am and lasts up to 12:00pm, in coincidence with the activity of the ceramic factory, 100m far from station OR. Hereonafter *Cp* and *Dp* indicate the low- (or calm) and high- (or disturbed) amplitude transients, respectively. Comparing spectra during *Cp* and *Dp*, the disturbance source is characterized by high values of noise amplitude above 1Hz and by two peaks at 3 and 5 Hz, particularly evident in the vertical component.
Applying the f-k analysis to the array data, the source backazimuth points to 320°, the same direction of station OR and the ceramic factory.
(b) HVNSR contour plots and HVNSR curves for station G2 calculated over the entire recording time (3 months).
For every day we considered an average of HVNSR calculated on a fixed hour (at 3:00am for *Cp* and 5:00am for *Dp*). At 5:00am the ceramic factory fully operates, except for weekends and holiday summer. Julian date from 214 to 244 corresponds to August.

The image plots at the top show that considering only HVNSR calculated on *Cp* there is a strong stability of HVNSR. On the contrary, using only HVNSR on *Dp* the weekly cycles of human activity as well as the summer holiday emerge.
The difference in HVNSR between *Cp* and *Dp* is particularly intriguing for the array station G2, that shows a sistematic shift of the frequency peak from 3.5 up to 3.9 Hz, and a correspondent increase in the amplitude, from 2.2 to 4.5. Although we believe HVNSR amplitude is not an indicator of seismic amplification, the variation of the resonant frequency indicate that the the stability of HVNSR over time is not guaranteed.
The HVNSR technique should be applied in very controlled experimental conditions, particularly difficult to achive in urban environments.

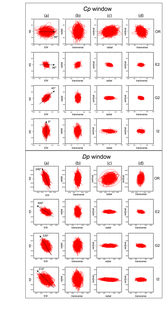


Spectra during *Cp* and *Dp* and effect on HVNSR
The analysis of the spectra recorded during *Cp* and *Dp* confirms the role of the ceramic factory as main noise source at Cavola. Moving away from the factory (from OR to P3) the *Dp* motion concentrates in the horizontal component, suggesting that attenuation and phase conversion could play an important role. In particular, *Dp* spectra for station G2 show a clear peak centred between 3 and 4Hz in the horizontal motion, whereas the vertical one is flat shaped and with a trough at 3.9Hz.

A possible key to understand the frequency shift found for station G2 is the noise wave-field composition and the moderate impedance contrast under the array.
During *Cp* noise sources are local (distance ranging from 10 up to 200m) and randomly distributed with respect to the array. Due to the short travel time, body waves attenuation cannot be very strong and the noise wave-field results as a mix of body and surface wave. On the contrary, during *Dp* the ceramic factory acts as a persistent and predominant noise source. The distance between station G2 and the ceramic factory is about 800m. Such a source, located on the landslide body, locally generates strong vertical pulses that travel towards the array area. These conditions are favourable to the generation of Rayleigh waves; after a few hundred meters body waves attenuate and convert mainly in surface waves that become the strongest component of the noise wave-field.



1D transfer function and ellipticity
A validation of our hypothesis on the composition of the noise wave-field at Cavola is given by the computation of the 1D transfer function for vertical propagating SH-waves and the ellipticity function for Rayleigh waves.
Following the previous observations, we think that the 1D transfer function should fit the HVNSR during *Cp*, whereas the ellipticity function should fit the HVNSR during *Dp*.
We used a velocity model based on the down-hole measurements at borehole2, that is close to the array station G2.
The two simulations match the frequency shift observed on HVNSR, while the disagreement in the amplification level confirms that HVNSR amplitude is not usable to infer amplification factors. The thickness variation along the source-station path can partially explain this mismatch.



Particle motions and polarization analysis
Our interpretation on the composition of the noise wave-field at Cavola is supported by the analyses of:
(a) particle motions (ppm) for the array stations E2, G2 and I2, both for *Cp* and *Dp*. Ppm are calculated for 100s-windows in the frequency range 2-5Hz.
(b) predominant polarization vector for stations OR, E2, G2 and I2, both for *Cp* and *Dp*. The polarization analysis is performed by means of the covariance matrix approach on 1-hour windows filtered in the frequency range 2-5Hz.
Both ppm and polarization analyses suggest that in the array area the ground motion during *Dp* is basically horizontal, quite stable and oriented between 300°and 340°, roughly corresponding to the azimuth of the ceramic factory. During *Cp*, amplitudes are lower than *Dp* and ppm are still mainly horizontal but with a variable predominant direction among the three stations. This observation can be related to the absence of a coherent wave-field propagating through the array.

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